Compton Polarimetry

Prospects for Polarimetry with the Advanced Compton Telescope

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<u>Outline of Talk</u>

Basic Principles

Experimental Status

Prospects for ACT

Basic Principles of Compton Polarimetry

Polarimetry relies on the fact that…

photons tend to
Compton scatter at right angles to
the incident polarization vector

$$d\sigma = \frac{r_o^2}{2} d\Omega \left(\frac{E'}{E_o} \right)^2 \left(\frac{E_o}{E'} + \frac{E'}{E_o} - 2\sin^2\theta \cos^2\eta \right)$$

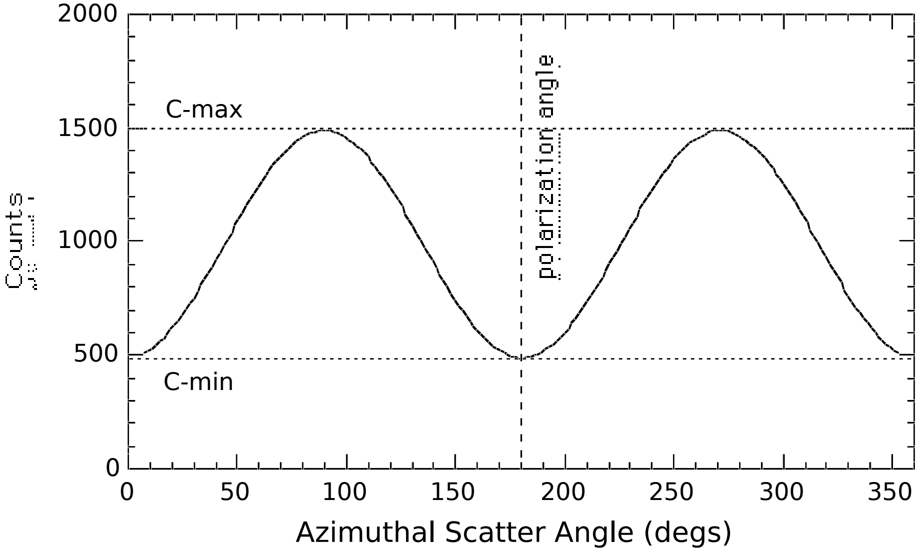
E'

θ is the Compton Scatter Angle

η is the Azimuthal Scatter Angle

The Polarization Signature

For a fixed Compton scatter angle (θ), the azimuthal distribution of scattered photons contains the polarization signature.



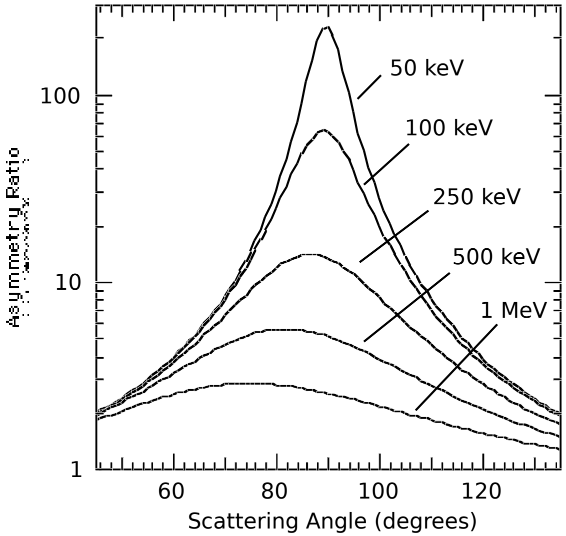
$$C(\eta) = A\cos 2(\eta - \phi) + B$$

The *amplitude* of the modulation defines the *level of polarization*.

The *minimum* of the distribution defines the *plane of polarization*.

Asymmetry Ratio

Defines the quality of polarization signature.



Ratio of max and min cross sections with respect to azimuthal scatter angle (η)

$$R = \frac{d\sigma(\eta = 90^\circ)}{d\sigma(\eta = 0^\circ)} = \frac{(E_o/E' + E'/E_o)}{(E_o/E' + E'/E_o - 2\sin^2\theta)}$$

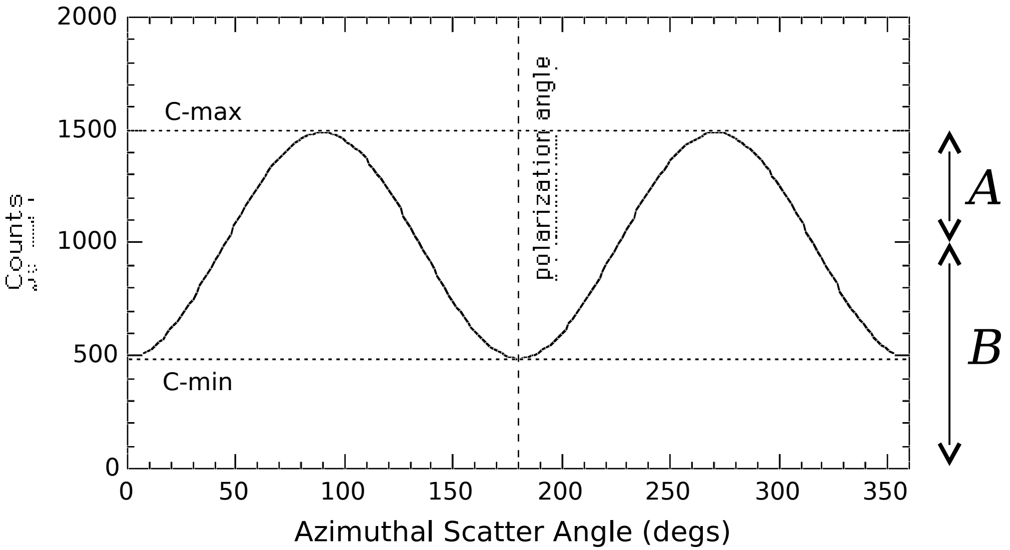
Important Features:

1. Ratio is very peaked wrt Compton scattering angle (θ)
2. At low-energies, ratio peaks near θ = 90°
3. Peak moves to smaller θ at high energies (≈ 45° at 10 MeV)

Modulation Factor

Modulation Factor for a 100% polarized beam represents a figure-of-merit for the polarimeter :

$$\mu = \frac{C_{max} - C_{min}}{C_{max} + C_{min}} = \frac{A}{B}$$



$$C(\eta) = A\cos 2(\eta - \phi) + B$$

The Polarization Measurement

Magnitude of the Polarization

$$P = \frac{\mu_P}{\mu_{100}} = \frac{1}{\mu_{100}}\left(\frac{C_{max}(P) - C_{min}(P)}{C_{max}(P) + C_{min}(P)}\right)$$

μ_{100} = the modulation factor for 100% polarized flux

μ_P = the measured modulation factor

P = the level of polarization

Polarization Angle

Corresponds to the minimum of the scatter angle distribution (ϕ).

Minimum Detectable Polarization (MDP)

$$MDP = \frac{n_\sigma}{\mu_{100} S}\sqrt{\frac{S+B}{T}}$$

S = source counting rate

B = background counting rate

T = observation time

μ_{100} = modulation factor for 100% polarization

Sensitivity can be improved by :

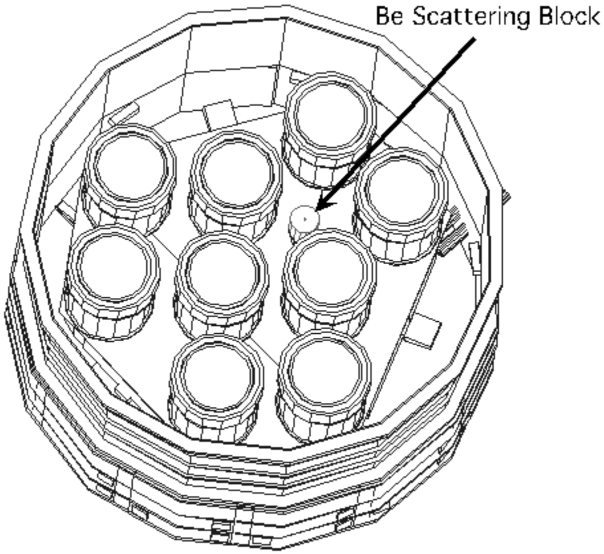
1) Increasing S (efficiency or geometric area)
2) Decreasing B
3) Increasing T
4) Increasing μ_{100} (optimize geometry)

Simulation Tools for Polarimetry

- EGS4 (LXeGRIT, GIPSI)
  - Low Energy Photon Transport Modifications (KEK)
- MCNP (TIGRE)
  - Polarization-dependent Compton cross-section (add-on)
- GEANT3 (GRAPE, HESSI, others)
  - Improvements to low-energy scattering physics (Kippen)
  - Polarization-dependent Compton cross-section (add-on)
- GEANT4
  - Polarization simulations should be possible by the end of this year (ESA / CERN collaboration)

High Energy Solar Spectroscopic Imager (HESSI)

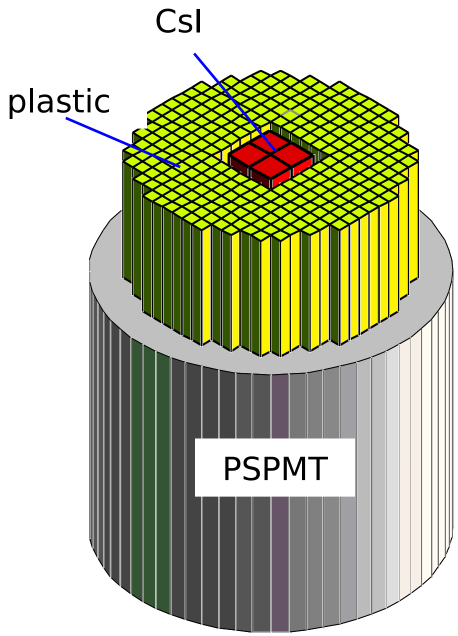
- Nine segmented Ge detectors
- Rotational Modulation Collimators
- Spinning spacecraft
- Small Be scattering block
  (3 cm diam by 3.5 cm high)
- Sensitive energy range 50 - 100 keV
- Polarization sensitivity < 10% for most X-class flares



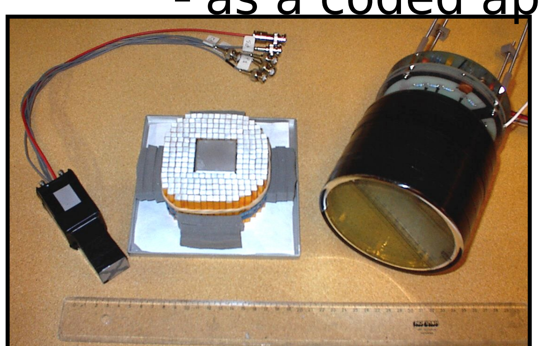
Current HESSI launch date : May 15

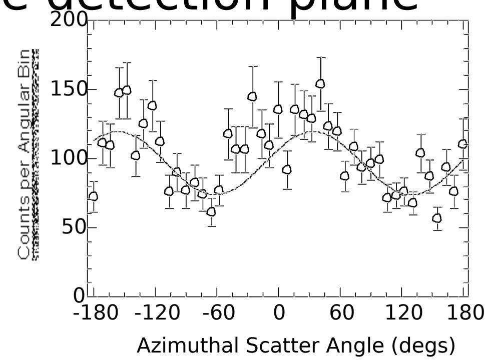
Gamma-Ray Polarimeter Experiment (GRAPE)

McConnell et al., *SPIE Proc.*, 3764, 70 (1999)



- Compact, modular design
- Prototype has been demonstrated
- Large field-of-view
- Useful for solar flares or γ-ray bursts
- MDP < 1% for X-class solar flares
- Could be used in imaging detection plane
  - as elements of a RMC system
  - as a coded aperture detection plane





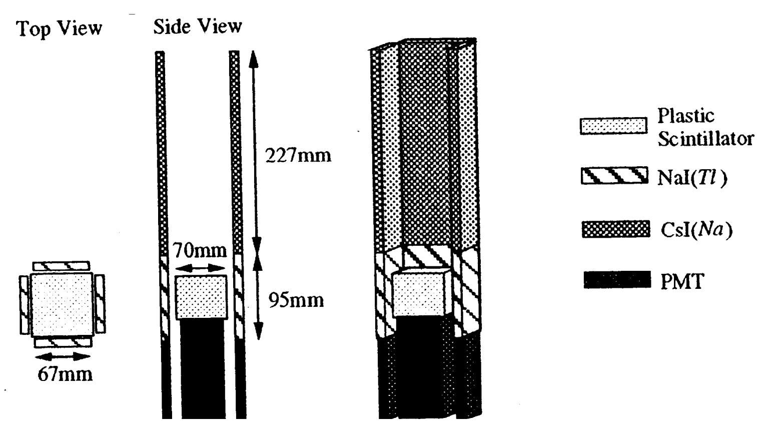
Polarimeter Development at Yamagata Univ.

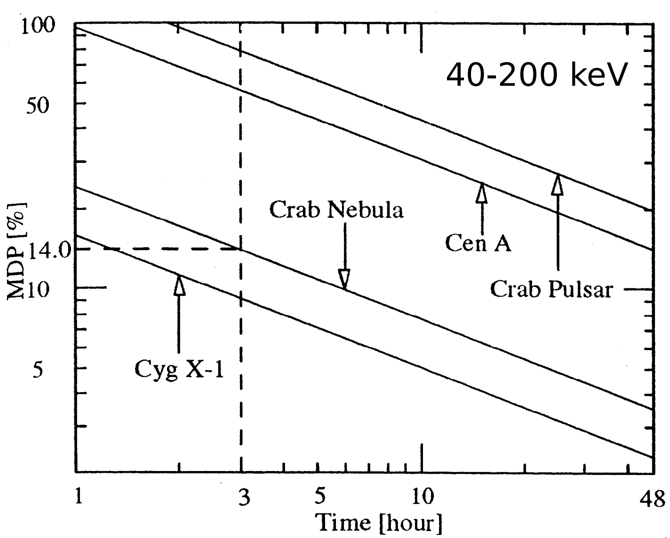
Tomita et al., *IEEE Trans. Nucl. Sci.*, 43 (3), 1527 (1996)

Arrays of plastic and NaI(Tl) elements.

PSD used to reduce background.

Full polarimeter consists of an array of nine elements.



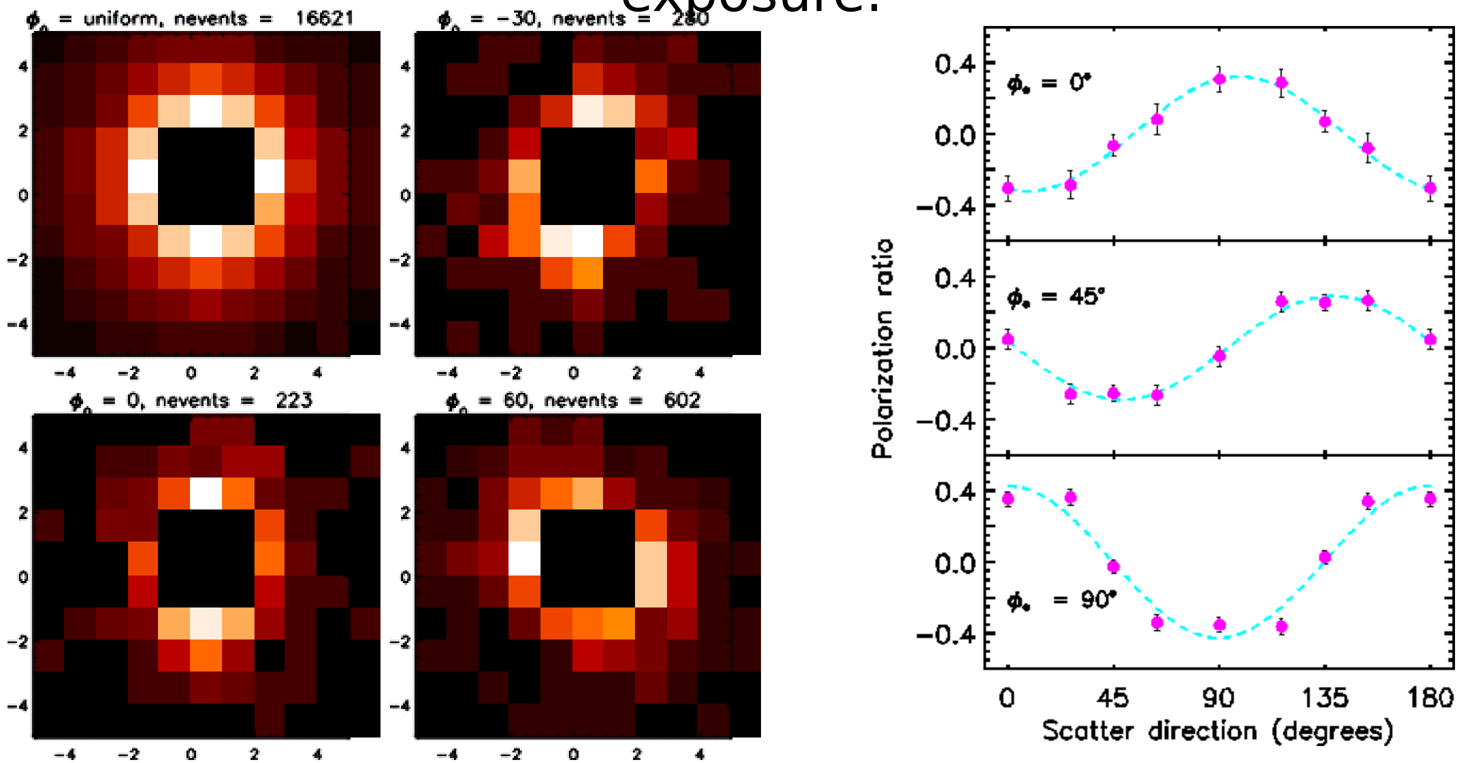


Gamma-Ray Instrument for Polarimetry, Spectroscopy and Imaging (GIPSI)

Kroeger et al., *NIM*, A436, 165 (1999)

Ge strip detectors, 1 cm thick, 2 mm strip pitch.

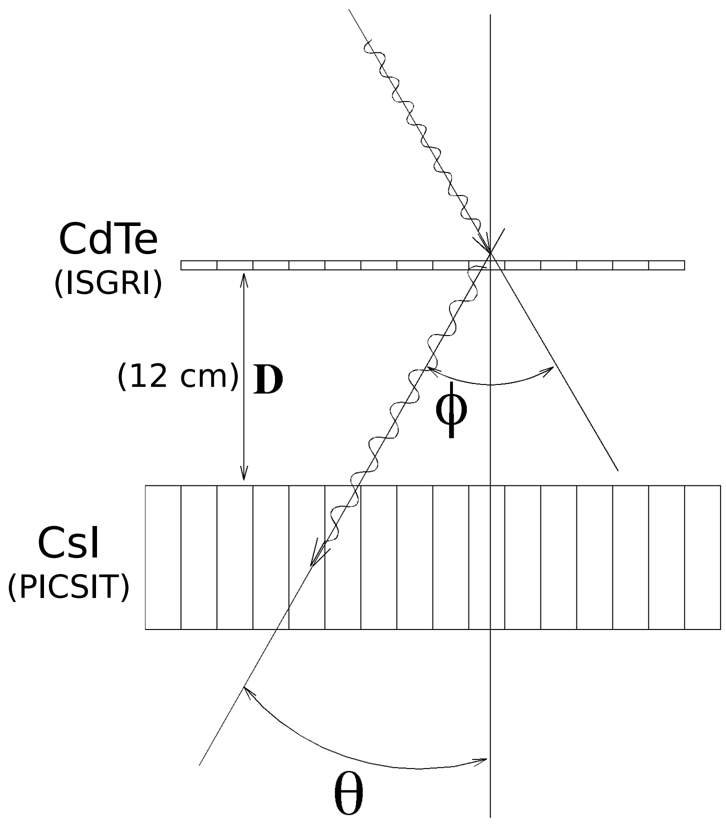
For a 400 cm^2 detector, polarization sensitivity < 5% on the Crab (70-300 keV) for a two-week on-orbit exposure.



Laboratory results at 290 keV

INTEGRAL / IBIS

Lei et al., *Proc. 2nd INTEGRAL Workshop*, ESA SP-382, p. 643 (1997)
Stephen et al., *GAMMA 2001* (this workshop)



PICsIT = PIxelllated CsI Telescope

ISGRI = Integral Soft Gamma Ray Imager

1) IBIS Compton mode

Always on.

Events scatter from CdTe to CsI.

Only single interactions in CsI.

Useful for transients.

2) PICsIT Polarimetry mode

Dedicated mode.

Events scatter from CdTe to CsI.

MDP on Crab :

200-500 keV ≈ 10%

500-1000 keV ≈ 20%

Coded Imager & Polarimeter for HE Radiation (CIPHER)

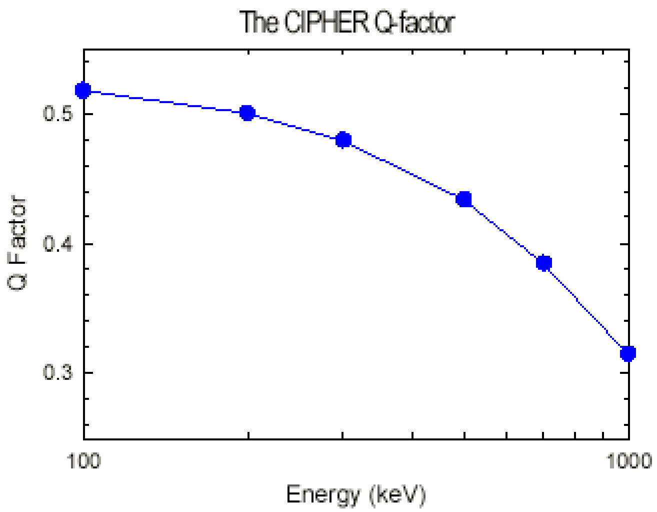
Caroli et al., *5th Compton Symposium*, AIP 510, p. 809 (2000)

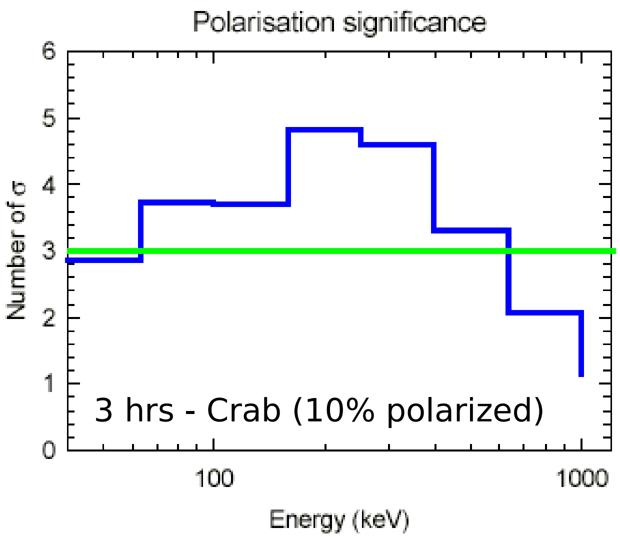
Balloon payload

Coded aperture imager (10 keV - 1 MeV)

CdTe imaging plane

Polarimetry relies on double scatter events in CdTe





Polarimetry with Compton Telescopes

Once the individual photon events are reconstructed, the analysis proceeds as follows :

1) Select events consistent with chosen sky region.
2) Select events within chosen energy range.
3) Select only those events with preferred range of Compton scatter angles (θ).
4) Analyze data with respect to the distribution of azimuthal scatter angles (η).

These selections not only optimize the source signal, but they also reduce the background.

Compton Telescope Geometry

The polarization signature is most pronounced at certain energy-dependent scattering angles (45° < θ [illegible]).

θ

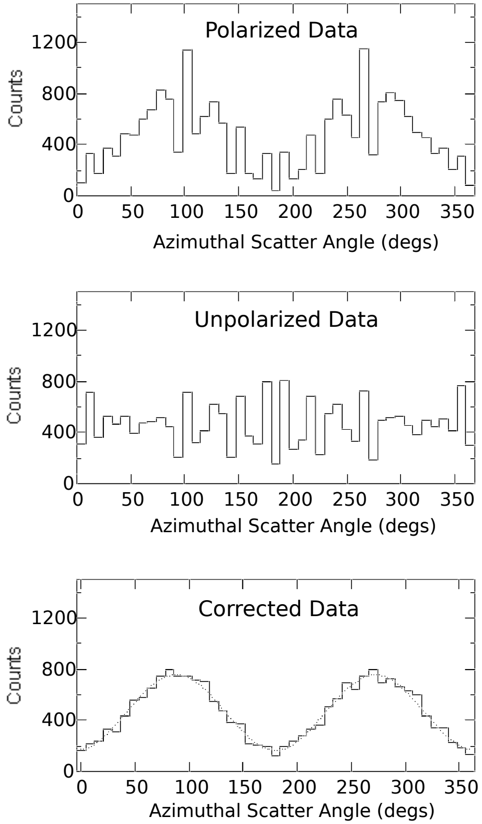
Good Geometry
(ACT, TIGRE,
LXeGRIT, MEGA)

Poor Geometry
(COMPTEL)

Systematic Effects in Polarimetry

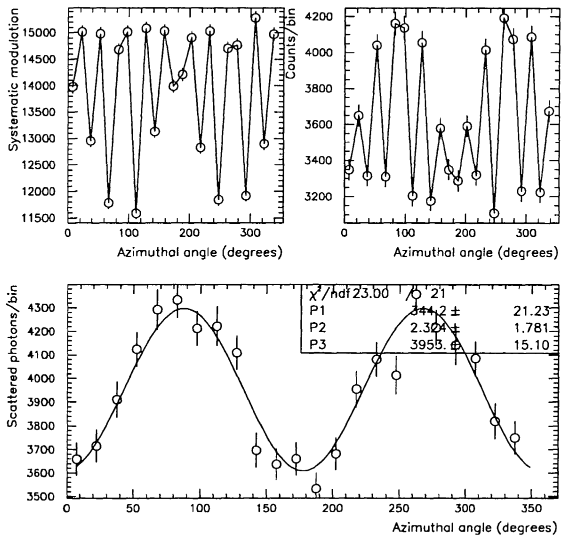
Even unpolarized beams may show asymmetries.

These asymmetries must be accounted for, either by rotation or by data correction.



GRAPE

(McConnell et al. 1999)



Simulated results at 1 MeV (θ = 0°)

COMPTEL

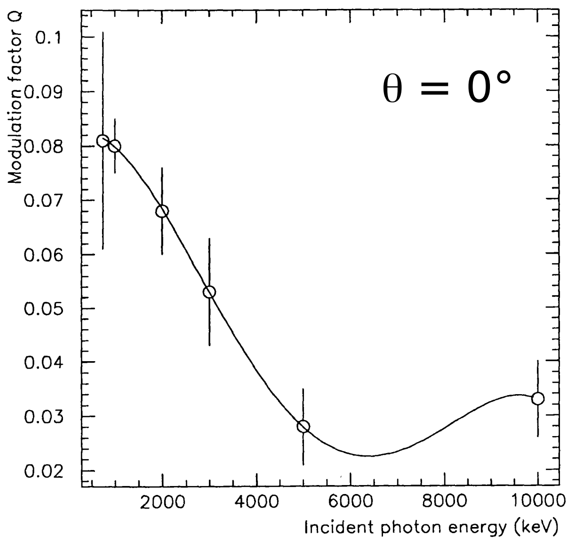
(Lei et al., 1996)

Polarimetry with COMPTEL

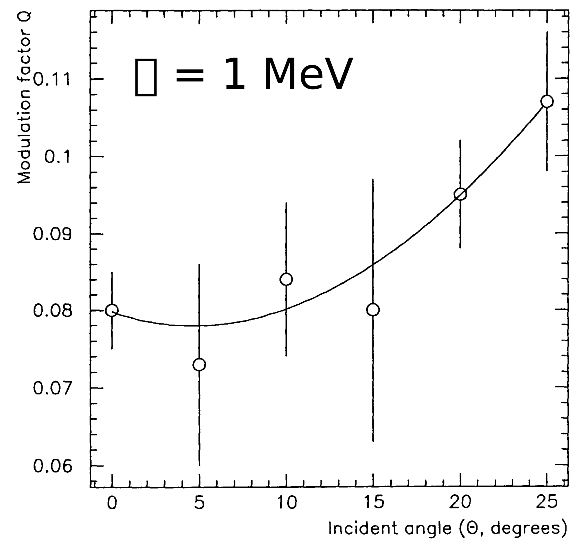
Lei et al., *A&AS*, C120, 695 (1996)

Poor geometry leads to small modulation factor.

Attempts to measure polarization of GRBs and solar flares have so far been unsuccessful.



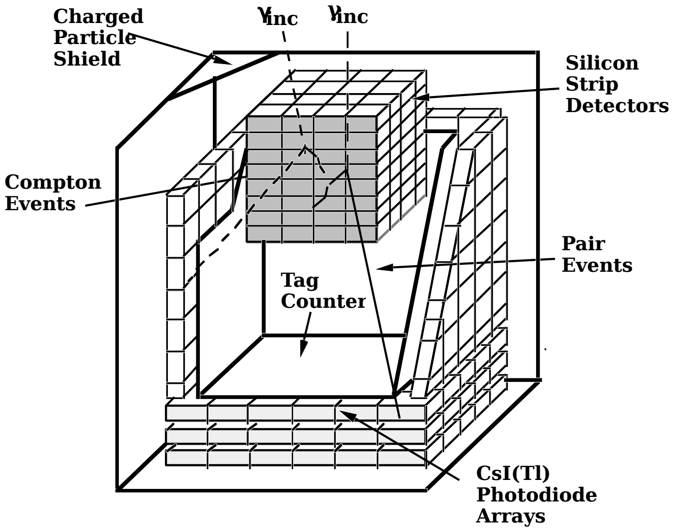
Modulation Factor vs. energy



Modulation Factor vs. incident angle

Polarimetry with TIGRE

Akyüz et al., *Experimental Astronomy*, 6, 275 (1995)

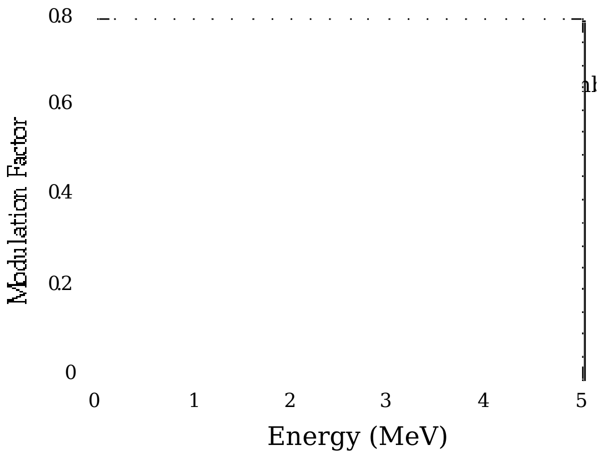


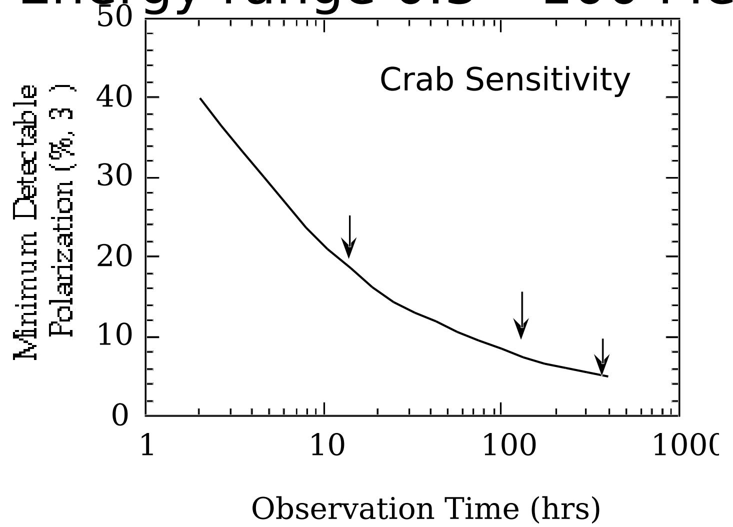
50 layers of Si strip detectors.

Each layer 13 cm x 13 cm x 300µm.

Atmospheric & CDG backgrounds.

Energy range 0.3 – 100 MeV.



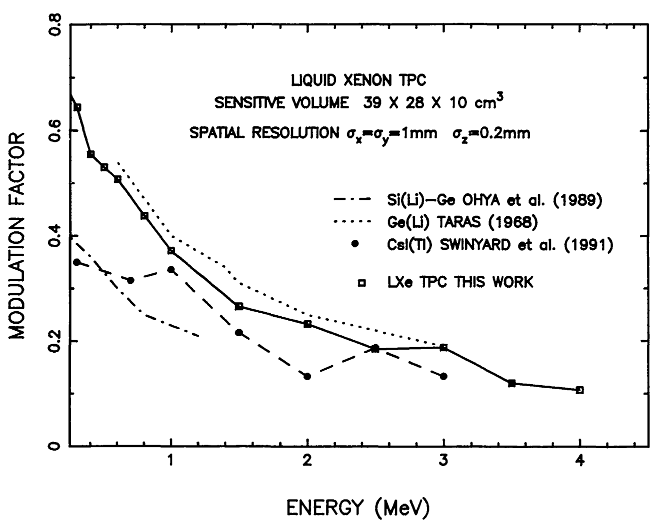


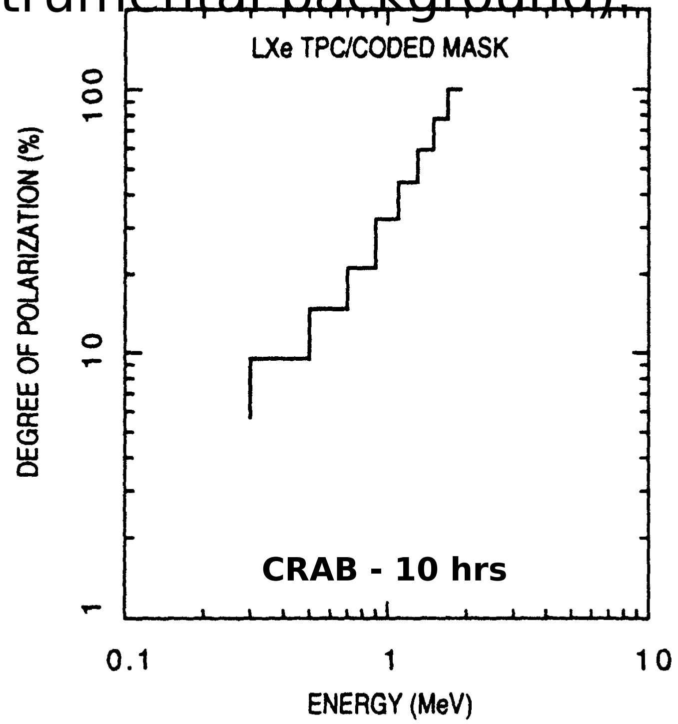
Polarimetry with LXeGRIT

Aprile et al., *ApJS*, 92, 689 (1994)

Simulations based on active Xe volume of 39 x 28 x 10 cm^3
(vs. 20 x 20 x 7 cm^3 for the current balloon instrument).

Background estimate assumes only atmospheric and CDG components (no instrumental background).

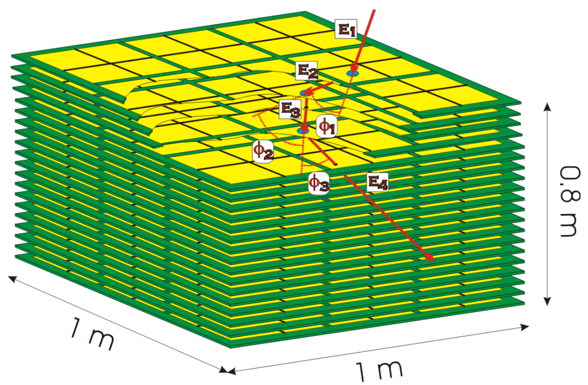




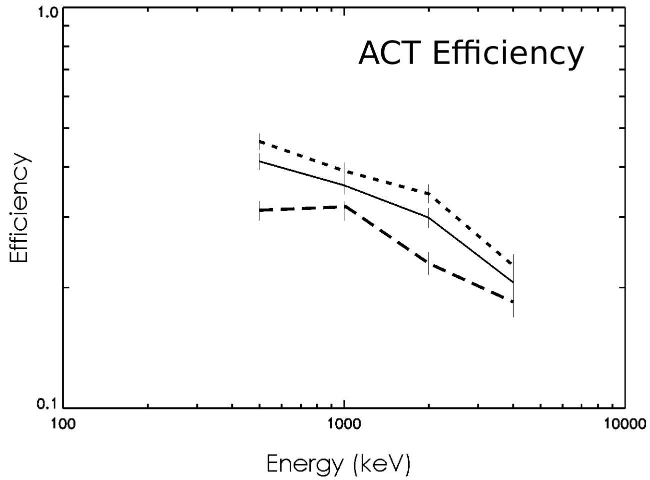
Polarimetry with ACT

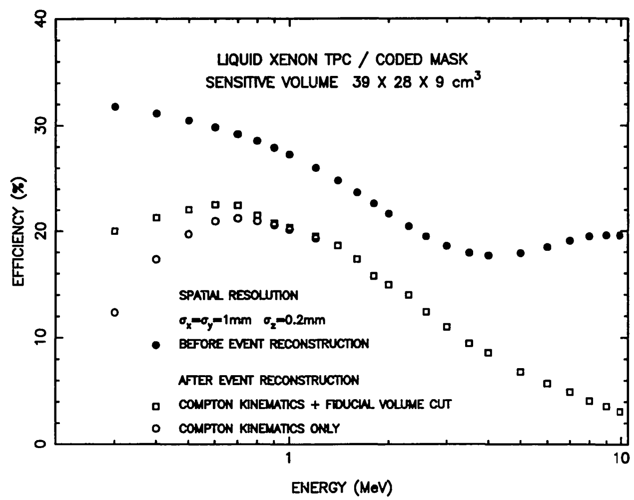
Baseline concept assumes:

1) Multiple layers of Si strip detectors
2) Each layer has 1 m^2 of active area
3) Total thickness of 35 - 40 gm cm^{-2}
4) Event reconstruction efficiency of 75%
5) Angular resolution < 10°

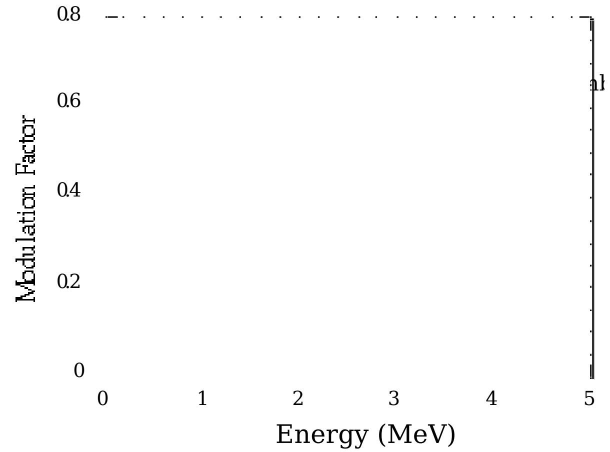


ACT Detection Parameters





Both efficiency and modulation factors are comparable to LXeGRIT.



Polarization Sensitivity Based on LXeGRIT

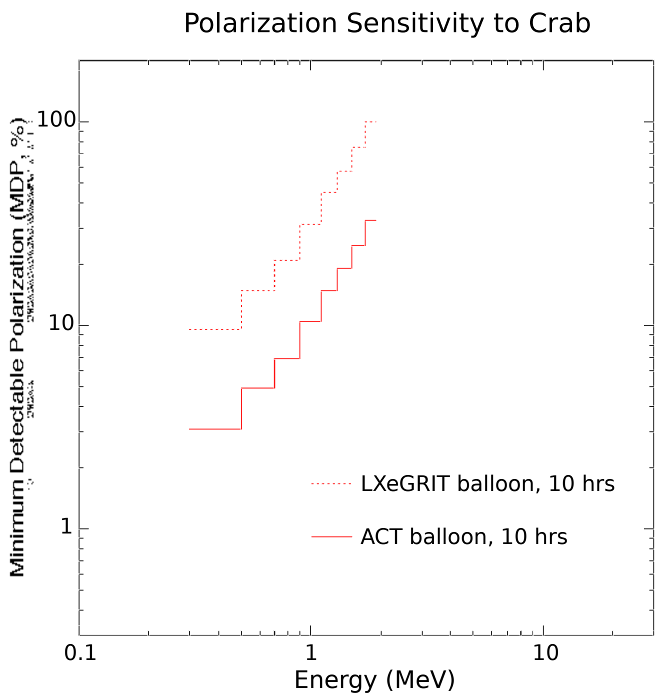
Extrapolated results from Aprile et al. (1994).

Assumes 10,000 cm^2 for ACT vs. 1093 cm^2 for LXeGRIT.

Assumes both source and background scale as area.

Assumes comparable efficiency and modulation factor.

$$MDP = \frac{n_\sigma}{\mu_{100} S}\sqrt{\frac{S+B}{T}}$$



Independent Polarization Sensitivity Estimate

$$MDP = \frac{n_\sigma}{\mu_{100} S}\sqrt{\frac{S+B}{T}}$$

Independent polarization sensitivity estimate assumes:

1. Event reconstruction efficiency of 75%.
2. Compton angle selection reduces # of events by 50%.
3. Modulation factor comparable to LXeGRIT and TIGRE.
4. Background dominated by cosmic diffuse (CDG)
5. Total background is twice the CDG flux arriving from within a solid angle cone of half-angle 10°.
6. CDG spectrum as measured by COMPTEL.

Polarization Sensitivity of ACT